

# DESIGN OF A COMPUTER-BASED CONTROL SYSTEM USING LABVIEW FOR THE NEMESYS ELECTROMAGNETIC LAUNCHER FACILITY\*

B. M. Huhman<sup>§ 1</sup>, J. M. Neri

Plasma Physics Division, Naval Research Laboratory  
Washington, DC USA

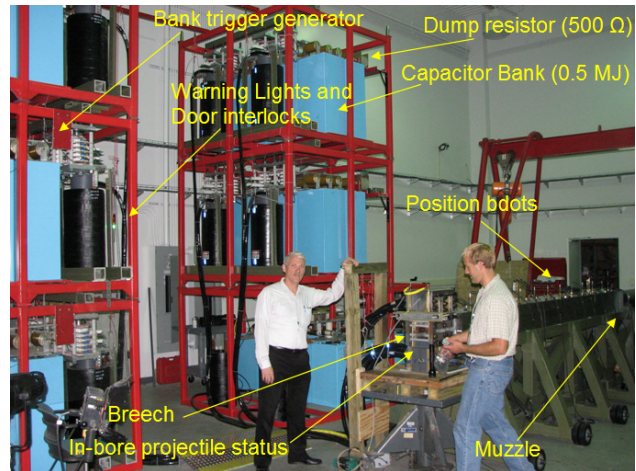
## Abstract

The U.S. Naval Research Laboratory has assembled a facility to develop and test materials for the study of barrel lifetime in electromagnetic launchers (EML) for surface-fire support and other missions<sup>1</sup>. The pulsed power system utilizes 12 500-kJ modules that can be individually triggered to shape the output current pulse<sup>2</sup>. Each bank module consists of four 130 kJ/can 11-kV capacitors from General Atomics Electronics Systems. The switching thyristors and crowbar diodes are from ABB. A series inductor of approximately 80  $\mu$ H is used to limit the peak current to 100 kA, isolate modules from each other, and ensure the current is delivered to the test system.

LabVIEW from National Instruments (NI) was selected as the control software for the EML system. All facility operations are handled through LabVIEW and controlled by a single operator. The software controls the safety systems; programs and monitors the three CCS High Voltage Power Supplies from General Atomics Electronic Systems; and triggers the capacitor banks. Projectile position status inside the barrel is also monitored in 25-ns steps using the PXI-7811R FPGA module. An overview of the EML facility with respect to control issues is presented. In addition to the software code, circuit diagrams of conditioning hardware will also be discussed. Results from test shots will be shown and discussed.

## I. LAUNCHER FACILITY REQUIRES PROCESS CONTROL FOR SHOT OPERATIONS

The current 5-MJ MTF EML Facility at NRL has over 100 data points that must be either monitored or controlled. After the upgrade in summer of 2007 to 11-MJ, the point count will double. In order to properly ensure the facility is operated in a safe and consistent manner, computerized process control software and associated hardware was investigated for integration into the facility. A picture of the facility is shown in Figure 1 with control items highlighted.



**Figure 1.** NEMESYS facility with 6-MJ capacitor banks and 4-meter barrel.

### A. Data Point Analysis

To determine the hardware and software capabilities needed, the data control points to be monitored were analyzed. Currently three high voltage power supplies from General Atomics (GA) are being used to charge the capacitors, with a fourth to be added after the upgrade. Each power supply has a number of digital input/output controls, plus analog voltage program with voltage and current feedback. In addition to the power supply data flow, controls were also needed for the isolation Ross relays that remove the power supplies from the charging circuit after the capacitor banks have reached the desired charge level. For safety reasons, the external interlock controls of the power supplies were connected to the status switch of the relays and tied into the emergency stop loop. If an emergency stop button was activated, a door was opened, or the relay was not energized, the power supply could not energize the high voltage output.

Each 0.5 MJ capacitor bank was analyzed as a separate system. In the initial build, 12 banks were used. A total of 22 banks will be controlled after the upgrade. Each bank has a dump relay that forces the bank to dump through a 500  $\Omega$  resistor to ground. Both the relay energize command and the status are considered data points. A voltage divider connected to the capacitor bank

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<sup>§</sup> email: [brett.huhman@nrl.navy.mil](mailto:brett.huhman@nrl.navy.mil)

<sup>1</sup> Formerly L-3 Titan Group, Reston VA 20190

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14. ABSTRACT <b>The U.S. Naval Research Laboratory has assembled a facility to develop and test materials for the study of barrel lifetime in electromagnetic launchers (EML) for surface-fire support and other missions<sup>1</sup>. The pulsed power system utilizes 12 500-kJ modules that can be individually triggered to shape the output current pulse<sup>2</sup>. Each bank module consists of four 130 kJ/can 11-kV capacitors from General Atomics Electronics Systems. The switching thyristors and crowbar diodes are from ABB. A series inductor of approximately 80 <math>\mu</math>H is used to limit the peak current to 100 kA, isolate modules from each other, and ensure the current is delivered to the test system. LabVIEW from National Instruments (NI) was selected as the control software for the EML system. All facility operations are handled through LabVIEW and controlled by a single operator. The software controls the safety systems; programs and monitors the three CCS High Voltage Power Supplies from General Atomics Electronic Systems; and triggers the capacitor banks. Projectile position status inside the barrel is also monitored in 25-ns steps using the PXI-7811R FPGA module. An overview of the EML facility with respect to control issues is presented. In addition to the software code, circuit diagrams of conditioning hardware will also be discussed. Results from test shots will be shown and discussed.</b>		
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outputs a 0-11 volt signal for monitoring of the bank charge voltage. This allows the operator to instantly see if an individual bank is functioning properly, as well as showing the progress of the charging process. The final data points on the capacitor banks are with the trigger generator. A fiber optic signal is used to trigger the ABB switch, which in turn sends out a high voltage pulse to the pick up loops on the thyristors to trigger the firing of the bank. A second fiber optic line is used to read status back from the trigger generator. An error is generated in the software system if a "fired" status is not generated.

The safety system is also included in the data points. Each door has a gravity interlock. If the door is opened, the latch falls down and has to be manually reset, even if the door is closed again. Each door has an individual status, as well as a daisy-chain. All of the doors must be in the closed state for the process to continue to the next step in the firing sequence. Four emergency stop buttons are also monitored in a daisy-chain sequence. If any one of the buttons is pressed, the system will stop.

A visual warning light system with audible sirens is also positioned around the facility. Three colors are used to indicate various system conditions. A green light is for when the system is de-energized and safe for all personnel to enter. A yellow light means the system is preparing to fire or a charge test is preparing to commence. Only authorized personnel such as operators are allowed in the facility. A red light indicates the system is energized, and is accompanied by a 90 dB siren. At this point, no personnel are allowed inside the facility. These indicators are automatically energized based on the current process control step.

A future safety system is the in-bore projectile status monitoring. In the six-meter build, the banks will most likely be ripple-fired to shape the current pulse. In the first two meters of the gun, b-dot monitors will be connected to the control system every 0.3 meters. As the projectile passes the monitor, the resulting voltage will cross zero and two separate monitors can be timed to obtain a velocity. Before a shot, a simulation will be run to determine the proper amount of time between markers. If the timing is not made after the selected time, the system will prevent the remaining capacitor banks from firing. If a timing mark is not made, most likely the projectile has become stuck in the barrel or broken up. In order to prevent further damage, the control system will prevent extra energy from being dumped into the problem area.

A number of miscellaneous points are also included, such as the gate valve in the flight tube, the vacuum pump valve in the catcher tank, and digital outputs for triggering the data acquisition system and the digital video recorders.

### **B. Selection of Control System**

There are two basic control systems that can be selected, Programmable Logic Controller (PLC) and Personal Computer-based (PC) packages. The PLC has

the advantage of being a hardware-based package that operates independently of the PC, with software packages to provide the initial programming and monitoring of the operations. A PC package relies on the computer for process control, but has more flexibility than the PLC, as PLC are typically designed for slow-moving manufacturing operations.

For most of the data points described, the PLC would be an appropriate choice. Monitoring of power supply status and controlling relays is what a PLC is made for. However, in order to implement the in-bore projectile status, a system that can process data quickly was necessary. A railgun shot typically occurs in less than 10 ms, and firing capacitor banks to shape the current pulse are in the 100s of  $\mu$ s. In order for the projectile status system to read data, interpret it, and act, the controller must be able to perform each step in the 100s of ns. PLCs are limited to the  $\mu$ s range, but Field Programmable Gate Arrays (FPGA) can run in ns steps.

The final selection was the National Instrument LabVIEW system. One of the available hardware packages is an FPGA, and the base clock allows for implementing programming steps in 25 ns blocks. Figure 2 shows the LabVIEW operator workstation.



**Figure 2.** LabVIEW operator workstation with status display on left and programming screen on right.

LabVIEW satisfied other criteria, such as easy to program, and easily expandable data points. The hardware is available off-the-shelf and is already set up in software, allowing the programmer to write just the process control, not an additional adapter program to talk to the hardware. A service contract is also available to receive automatic software upgrades and on-demand engineering support.

## **II. PROCESS CONTROL HARDWARE DEVICES**

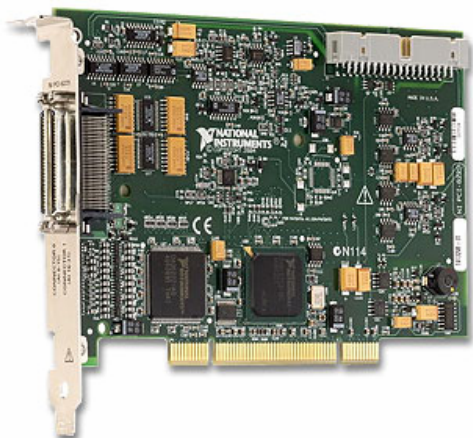
Three basic hardware devices were selected for the control system. Each device has a number of sub-devices attached that extend the capabilities of the device. All of the devices were commercially available from National Instruments and required a minimum amount of



installation before they were integrated into the control system.

#### A. PCI-6229 M-series Data Acquisition Board (DAQ)

For the high voltage power supplies, a dedicated board was selected to provide communications between the PC and the power supplies. The PCI-6229, shown in Figure 3, was selected due to the number of analog inputs and outputs available on the card. It has four analog outputs, 32 analog inputs, and 70 digital input/outputs (software configurable). It is the ideal control board for four power supplies, as each one requires only one analog output. The remaining data points are more than sufficient for the feedback data from the power supplies.



**Figure 3.** 6229 Data Acquisition (DAQ) card on PCI form factor.

For the analog data points, an isolation system by Dataforth is used to provide over-voltage protection to the DAQ board. Each Dataforth module (SCM5B31) will input a 0-10 V signal and output an exact 0-10 V signal. In the event of a power supply fault, any extraneous signals would destroy the individual module and not damage the DAQ card, and by extension, the PC. The digital data points go through optocouplers between the power supplies and the DAQ card, much in the same manner as the analog data points. National Instruments provides off-the-self isolation, but it is economically unviable, as one must purchase a card for each data point, not as a group.

#### B. PXI-7811R Digital Intelligent DAQ board with FPGA

The capacitor banks and the in-bore projectile status system are all based on the PXI-7811R FPGA card. The card is housed in an external four-slot PXI-1031 chassis, with a fiber optic link to the host PC. A number of expansion chassis are connected to the PXI-7811R.

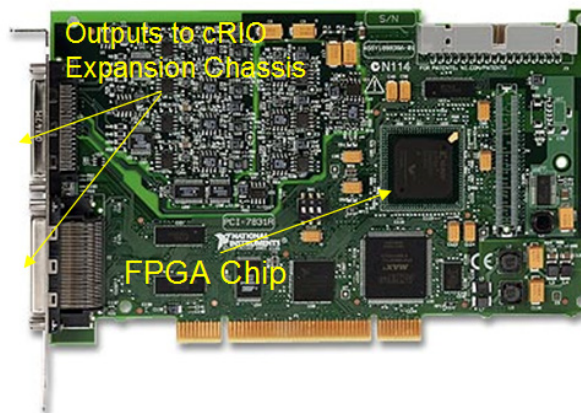
Initially, the data points were connected through several SCB-68 connector blocks, which provided no isolation between the FPGA and the outside world. After some problems, the system was migrated towards using cRIO-

9151 expansion chassis. Figure 4 shows the PXI chassis with the FPGA card and the cRIO expansion chassis.



**Figure 4.** FPGA in PXI chassis and cRIO expansion chassis with expansion cards.

The advantage of the chassis is two layers of isolation between the FPGA and the data points it controls. The first layer is the chassis, and the second is the module that actually provides the digital or analog function to the data point. An interesting feature of the chassis system is one can actually add more data points than the FPGA would have with the connector blocks. The PXI-7811R, shown in Figure 5, normally allows only 140 digital input/output (DIO) points, but with the expansion chassis the theoretical limit is 512, with a 32-channel module in each four-slot bay with the maximum four add-on chassis attached. In addition, analog modules can be added to a digital-only FPGA board. The cable between the chassis and the FPGA becomes a communications bus, whereas before it was strictly each data point was a wire in the cable.



**Figure 5.** 7811R FPGA card with PXI form factor.

A major feature of the FPGA is the ability to have multiple program loops running simultaneously, and they can even be running at different clock rates, while in a normal controller each loop must wait for the previous loop to finish before it can run its tasks. This allows for the in-bore position status monitor to run as fast as

possible and not be interrupted by a separate task that waits for input from the operator.

The FPGA communicates easily with the host PC program, transferring data back and forth through a communications bus created in software. The FPGA is programmed using the standard LabVIEW interface, but does require the purchase of a separate software package. The new software includes a compiler that translates the high-level LabVIEW code into low-level Xilinx language, eliminating the need for learning VHDL.

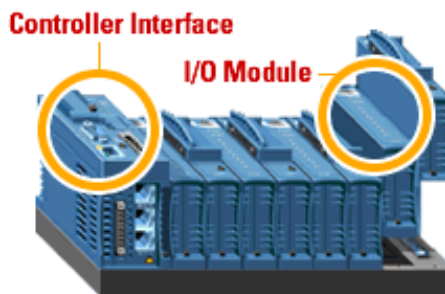
In the initial build, three NI-9401 8 channel bidirectional 5V/TTL modules were used for digital input data. Since then, NI has produced a 32 channel bidirectional 5V/TTL module, the NI-9403. For the upgrade, this module will be used. It is slightly slower, 7  $\mu$ s vs. 100 ns, but it is within tolerance for monitoring relays and capacitor bank trigger status.

Each module can be configured for input or output, in four channel sections. One NI-9401 was partially configured in the digital output mode to trigger the data acquisition system and command the digital video recorders to start recording.

A single NI-9476 32 channel 6V sourcing digital output module was used for commanding the dump relays on the capacitor banks to energize and for firing the capacitor banks. The relay control is through a Grayhill 5V logic to 120VAC relay system, using G5-style modules. The Grayhill module prefers the output to be an open collector, so an intermediary box is between the NI-9476 and the Grayhill with open-collector optocouplers. In the expansion build, the NI-9476 will be replaced with a NI-9425 32 channel sinking digital output module, with the open collectors built into the device. This eliminates the intermediary board, and any potential problems with the optocouplers. The device can handle up to 60 VDC continuously or 1000  $V_{RMS}$  for five seconds, which is equivalent to the optocoupler.

### C. Compact Fieldpoint Rugged Ethernet Controller Interface

The Compact Fieldpoint (cFP) family of modules from NI is designed to be used in rugged, industrial applications. Similar to the cRIO-9151 chassis, individual modules can be purchased with specific purposed, such as analog input, digital output, or thermocouple interfaces. The cFP, shown in Figure 6, consists of a backplane, a controller interface, and input/output (IO) modules. The IO modules are hot-swappable, and can be removed and added without interrupting operations. Additional isolation can be achieved between the cFP unit and the host PC by using an Ethernet to fiber optic converter.



**Figure 6.** Compact Fieldpoint system diagram with controller, backplane, and I/O modules.

While the controller can be configured to run autonomously, for this application it is controlled by the host PC. Unlike the FPGA, the cFP system is always running. Using the NI Measurement and Automation Explorer (NI-MAX), the operator can look at a live raw data feed, and even manually operate the relay outputs without having to run the host PC program. This is a substantial advantage for facility operations, as occasionally a valve or a particular system needs to be powered for a local test. The FPGA can only operate when the host PC program is running, which is sufficient for operations such as bank trigger testing and operating dump relays.

The voltage feedback from the capacitor banks is digitized through AI-118 eight-channel isolated analog input modules. Each module features 16-bit resolution, 750  $V_{RMS}$  channel-to-channel isolation, 2300  $V_{RMS}$  channel-to-backplane isolation, and input voltage ranges of 0 to 1, 0 to 5, 0 to 10, 0 to 15,  $\pm 1$ ,  $\pm 5$ ,  $\pm 10$ , and  $\pm 15$  volts. Before the voltage feedback enters the AI-118 modules, the signal goes through a Dataforth module, similar to the power supply analog data, to ensure the channels on the AI-118 module are protected from surges.

A number of relays are controlled through the cFP modules, using the RLY-425 module. Each digital output is a single-pole single-throw (SPST) normally open relay, and can handle up to 5 amps per channel. When directly actuating a relay, it is important to note that a flyback diode must be used to prevent damage to the channel after switching off an inductive load. Some of the data points on this device are warning lights, the gate and vacuum valves, and controls for powering various devices.

The digital inputs for the safety system are digitized through a DI-300 24VDC sinking digital input module. The status of various doors and the emergency stop daisy-chain are on this device.

After the system is upgraded to 11-MJ, a cFP-1808 eight-slot Ethernet backplane will be added to accommodate additional datapoints. The cFP-1808, unlike the cFP-2000, does not require a controller interface to function. It uses the built-in Ethernet interface to communicate with the host PC. Additional analog input and digital output modules will be added for monitoring of the new capacitor banks.



### III. DATA ACQUISITION SYSTEM

The data acquisition system consists of several devices, with the digitizers to record data and auxiliary devices to ensure the data is recorded in a meaningful manner. A software program developed at NRL is an essential component, as it integrates data acquisition, analysis, and archiving into one package.

In parallel to the data acquisition system, LabVIEW is programmed to automatically record various system values during a shot sequence every 100 ms. Typical values include capacitor bank voltages, relay status and command value, warning lights and safety interlocks, power supply feedback and commands, and capacitor bank timing delays. The resulting file is recorded to a Comma Separated Values (CSV) file, which can be seamlessly integrated in to Microsoft Excel or another spreadsheet program. The data log provides an automatic database for tracking unusual events, debugging, and recording shot settings for later use in analysis.

#### A. Primary Data Acquisition Device

The primary data acquisition device is the VT1564A four-channel digitizer by VXI Technology, shown in Figure 7. Each channel features 14-bit independent analog electronics and isolation, with 800 kSamples/sec per channel. The maximum range of each channel is 256 volts. The VXI digitizers are designed for environments with high levels of electrical noise, as evidenced by the twinaxial connectors for each channel. In the current build, 56 channels are available for use, and the system can be upgraded to 96 channels by purchasing additional digitizer cards to fill empty slots in the second chassis.



Figure 7. VXI VT1564A four-channel digitizer cards in VXI chassis.

#### B. Data cables

To reduce signal noise, twinaxial cables are the preferred method of transmitting signal data from a probe to the digitizer. These are shielded twisted pair cables, with the undesired current shunted to ground via the guard shield. The VXI digitizers are designed to accept the twinaxial data cables. In cases where maximum isolation between the digitizer and the probe is desired, fiber optic analog links are used to transmit the data, as shown in Figure 8. The Nicolet Isobe 5500 links are scalable to various voltage ranges. The remote links operate on a battery to isolate the electronics from the building power supply.



Figure 8. Nicolet Isobe 5500 fiber optic data links for optical diagnostic isolation.

#### C. Primary and secondary trigger systems

Two independent trigger paths are used to ensure the data acquisition system is triggered. The primary trigger is a trigger pulse from the LabVIEW control system, with the falling edge (due to a VXI limitation) enabling the data acquisition. After a “fire” command has been given through the LabVIEW interface, a 5V/TTL pulse with a width of 1.0 ms is transmitted to a trigger distribution box, which replicates the trigger signal to up to 12 devices.

The secondary trigger, shown in Figure 9, detects a premature firing sequence in the capacitor banks. For normal operation, the unit will pass through the LabVIEW trigger pulse. If current is detected in the rogowski coils in the breech, it will generate a trigger pulse to activate the data acquisition sequence. This allows for the facility to record data even if an erroneous event occurs.

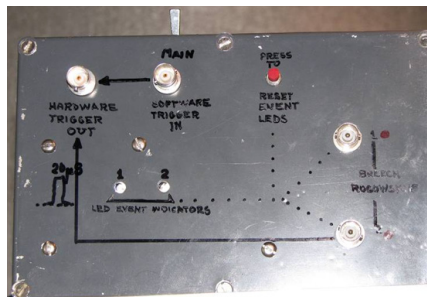


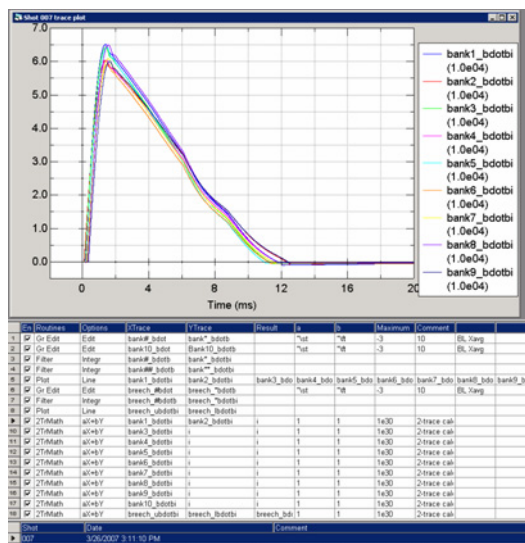
Figure 9. Secondary trigger for data acquisition triggers digitizers if current in breech rogowski coils is detected.

#### D. Data acquisition software

A software program has been developed by Code 6770 at NRL to acquire, analyze, and archive data from plasma physic experiments. The program, called “Stella”, provides three general functions: data acquisition, including configuration and operation of a variety of devices (primarily, but not limited to, the IEEE-488 bus); data analysis, including a wide variety of scalar, waveform, and image processing routines; and data archiving, including organization, annotation, presentation, and conversion to/from other formats as needed.

NRL developed the code in-house because many of the capabilities summarized above are not available in commercial programs. It was deemed more efficient in the long run to have a code specifically tailored to our requirements, and capabilities are added as needed. The coding architecture was designed to be easily extensible, with four formats for user-written plug-ins. Code components conforming to these specs can be loaded and linked dynamically at run-time, and thereafter function as integral parts of the program.

Stella was modified to allow direct control of the VXI digitizers through the IEEE-1394 (Firewire) bus. Each channel can be easily edited, adding details such as calibration data, cable number, and comments. Post shot analysis can be quickly performed using user-defined macros. Macros are frequently used options such as baselining, integration, and plotting that are configured via a spreadsheet-like interface. Once defined, macros can be run as a one-touch option. Different macros can be defined for different data, such as timing test data and shot data. An example of a data plot with a macro defined is shown in Figure 10.



**Figure 10.** Stella data analysis package with data plot and example macro.

After a shot is recorded, the data is saved in a folder-style database, with individual traces as separate files

inside the shot folder. Other users on a network can view these traces and run separate data analysis. Saved macros are automatically shared across all users. This system allows for a greatly increased efficiency in after-shot analysis.

#### E. Digital Video Recording (DVR) system

The facility is monitored via a closed circuit television (CCTV) system. Six color cameras are located in strategic locations around the main test cell. Two cameras are focused on the capacitor bank stacks, one each are focused on the breech, muzzle, catcher tank, and the whole room. A monitor is located in the control room for real-time monitoring of the facility. During a shot, two DVRs record the video stream from the cameras.

The DVRs from EverFocus provide simultaneous recording of all six cameras during a shot. The frame rate averages about 20 fps on the primary DVR. A secondary DVR is used to record high-frame rate (60 fps) of a select video feed. Currently the muzzle is selected for the higher frame rate. Each video recorded in MPEG-4 compression with a time/date watermark, which is downloaded to a PC for editing and archiving. An audio channel is also recorded from a condenser mike located in the test cell, and is mixed with a second condenser mike located in the control room. The microphones allow for post-shot analysis of unusual sounds.

On several occasions the video surveillance system has been used to identify problems during a shot, as shown in Figure 11. Since many events happen too fast for an operator to notice, being able to play the video back is invaluable. Typically a problem is noticed on the breech, but several times cable connection problems on the capacitor banks were identified before they became serious issues.



**Figure 11.** Image from CCTV system during unusual event in the breech and used for later troubleshooting.

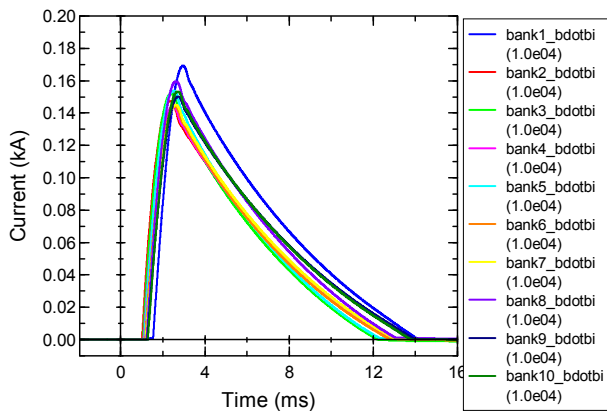
### IV. SYSTEM PERFORMANCE

The initial build with a 5-MJ capacity has been shot 53 times since coming on-line in March 2007. In July 2007



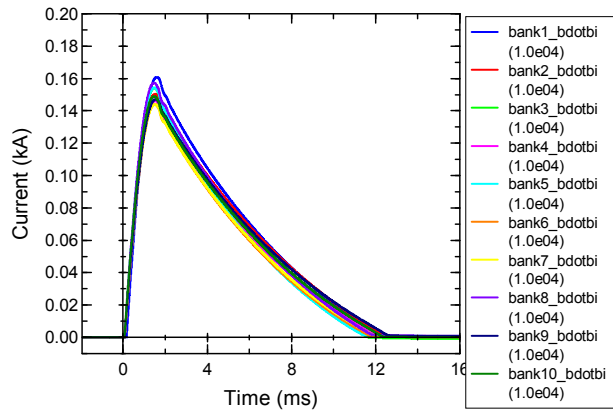
the system was taken offline to perform an upgrade to 11-MJ. In the first 53 shots, the system was operated for the majority of the shots in zero-delay mode, with all of the banks firing simultaneously. A few shots were performed with several banks triggered after the main sequence.

For shots without triggering delays, jitter was observed on the firing of the capacitor banks, as shown in Figure 12. The initial construction of the fiber optic trigger boards did not include any noise filters, but after random firing of the banks, an RC filter was introduced to attenuate noise induced on the signal lines. After the filters were introduced, the jitter started to appear. At first, it was assumed that the filters were causing the delays, as they were random and no bank had the same delay two shots in a row.



**Figure 12.** Capacitor bank currents during a low-voltage shot showing jitter on the initial triggering.

Originally, the program in LabVIEW that fired individual banks had a separate program loop for each bank, and they all looked at a common variable to trigger the banks. A revision of the program removed the individual loops and created a single loop. Each iteration of the new loop looks at all of the values for the bank delays. If a bank had a delay of 0 ms, that bank would fire on the current loop. After the loop was finished, all of the delay values were decremented by 100  $\mu$ s before the next iteration of the loop. After all of the banks reached 0 ms, the loop would exit and end the firing cycle. As shown in 13, with the exception of Bank 1, all of the banks are now firing simultaneously with no jitter. It is suspected that the control board for Bank 1 is faulty.



**Figure 13.** Capacitor bank currents during a low-voltage shot with software trigger revision.

To further eliminate noise problems, the fiber optics will no longer be located at each bank. They will be on a single monolithic board in the control room. Command fire and status fibers for all 22 banks will terminate at the new board, and converted to electrical signals close to the NI system for minimization of interference.

Electrical noise also interfered with the data acquisition trigger line. Initial tests with the system did not show any problems, but it is suspected that after the GA power supplies reach a certain voltage level they emit noise on the charging cables. After a number of spurious trigger signals, the trigger was reinforced with a trigger generator in the control room and two 6 db attenuators in series inside the screen room. The trigger generator creates a 20 volt pulse which is reduced to 5V after the attenuators. After the noise control implementation, there have not been any problems with noise on the data acquisition trigger line.

## V. SUMMARY

The initial 5-MJ build of the NEMEYS MTF launcher fired 53 shots from March 2007 to July 2007. NI's LabVIEW system has performed its function well, without any significant problems. Any small issues that came up were quickly and easily resolved, without any impact on shot schedule.

Noise isolation was a problem during the initial system start-up, but it has been resolved. Primary trigger noise was resolved with attenuators inside the screen room with the digitizers. Bank trigger jitter is believed to be caused by noise filters installed after noise caused premature bank firings. This issue will be addressed in the upgrade with a single electrical-to-fiber board located in the control room with fiber optics to each capacitor bank, and a revision of the trigger software.

The selected NI hardware and software performed their duties without any problems with data point incompatibility. During the upgrade to 11-MJ some slight modifications will be made to cRIO hardware. Some

additional modules will be added to the cRIO and cFP hardware, which will be automatically recognized by the NI software and ready to be integrated into the process control within minutes of installation. The upgrade was known from the start, and program stubs were created to accommodate the new data points.

The data acquisition system performed well. Data from the VXI digitizers in conjunction with video and the shot data log are preserved in a data archival system for later access for analysis.

## **VI. ACKNOWLEDGEMENTS**

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## **VII. REFERENCES**

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